Comparisons of Experimental and Simulated Turbulence Quantities

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Collaborators

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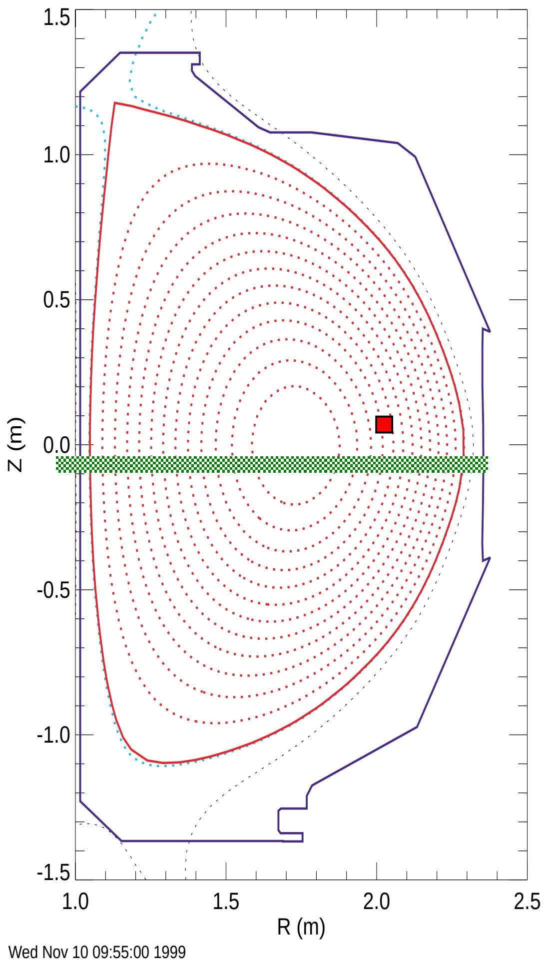
Today's presentation

- Current and near future turbulence diagnostics on DIII-D.
- Some mechanics of comparisons.
- Example of diagnostic issues using FIR scattering as well as illustrating new diagnostics coming on line.
- Data from correlation reflectometer system
  - Comparison to UCAN
  - Preliminary comparison to GYRO
  - Also new data from NSTX
- Some observations and issues from an experimentalist's perspective.

Current and near future DIII-D turbulence diagnostics

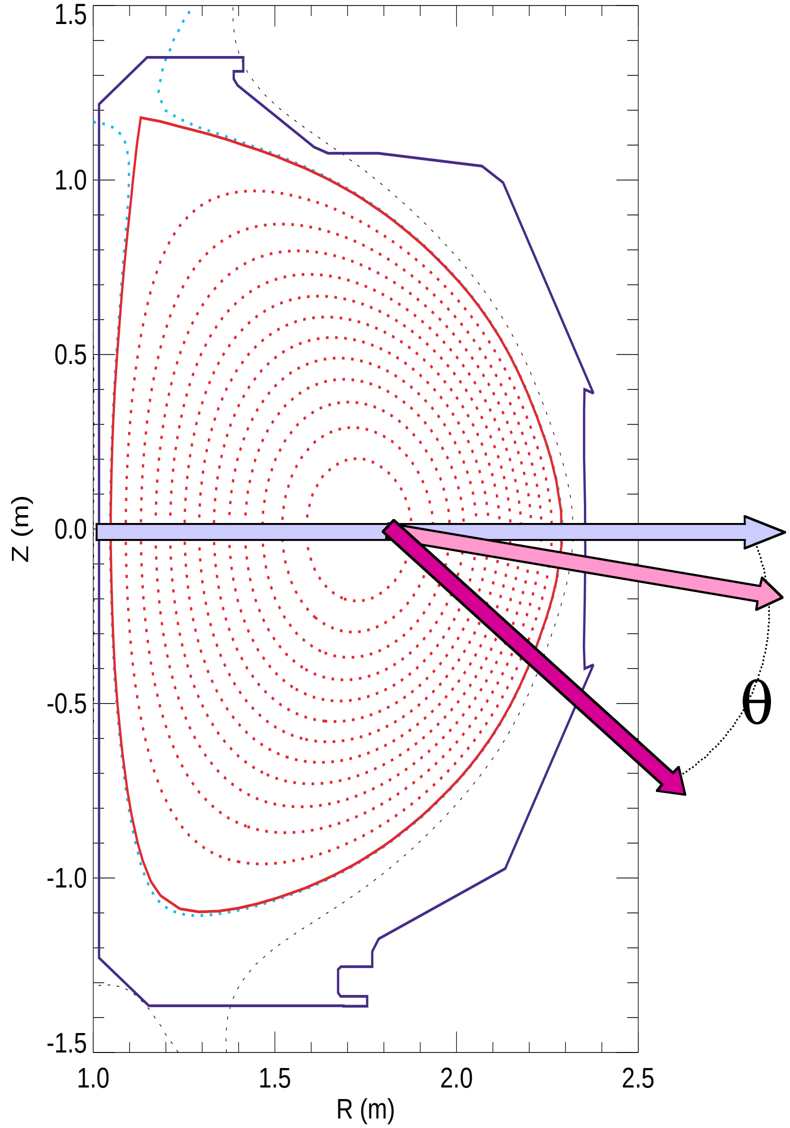
Diagnostic	**Example limitations**	**Measurements**
FIR scattering	Chord averaged	$\tilde{n}$, k_θ
PCI (phase contrast imaging)	Chord averaged	$\tilde{n}$, Δr
Reflectometry	Location is profile dependent	$\tilde{n}$, Δr, k_θ, V_θ
BES (beam emission spectroscopy)	Need NBI	$\tilde{n}$, Δr, k_θ, V_θ
ECE (electron cyclotron emission)	Long time average	T_{tilde}, k_θ, V_θ
Langmuir probes	Edge plasma	$\tilde{n}$, ϕ_{tilde}, T_{tilde} Γ, Q, k_θ, V_θ
Magnetic probes	Edge plasma	B_{tilde}, $k_\parallel$, k_θ
Polarimetry (future)	Chord averaged	B_{tilde}
High-k scattering (future)	Under development	$\tilde{n}$, k >10 cm^{-1}, $k\rho_s > 1$

Mechanics of Comparisons

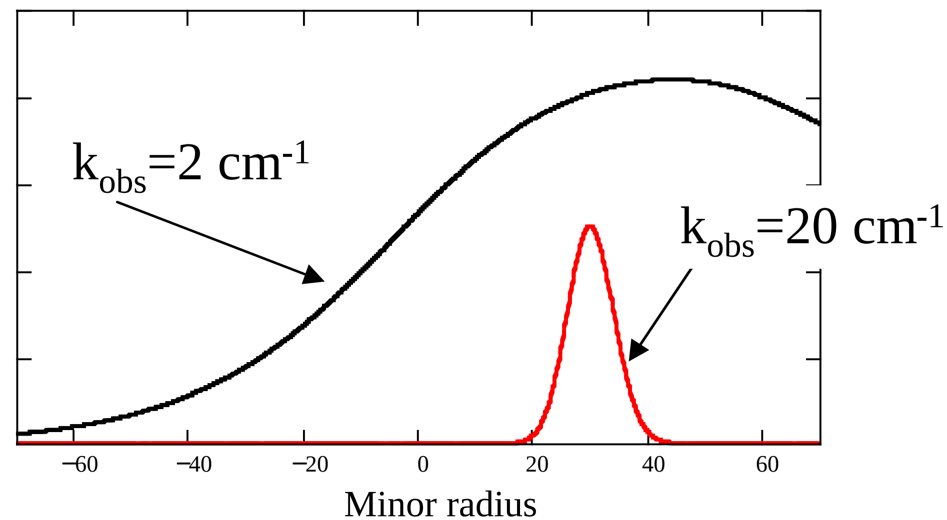


- Implement numerical diagnostics that simulate real world experimental measurements and analysis techniques.
  - Examples: local ñ wavenumber/frequency spectra, magnitude (e.g. via reflectometry, beam emission spectroscopy), chord averaged ñ with narrow k response (FIR scattering), local heat transport, etc.
- Simulated diagnostics use similar localization (or lack thereof), wavenumber/frequency response, detection position within the plasma,
  - Use similar data analysis techniques, including FFT's, correlation analysis, normalizations, etc.
- Work in this area ongoing and more recently includes
  - D. Ross, U. Texas, et al., compare BES, simulation
  - B. Nevins, LLNL - synthetic diagnostics

Example: FIR scattering

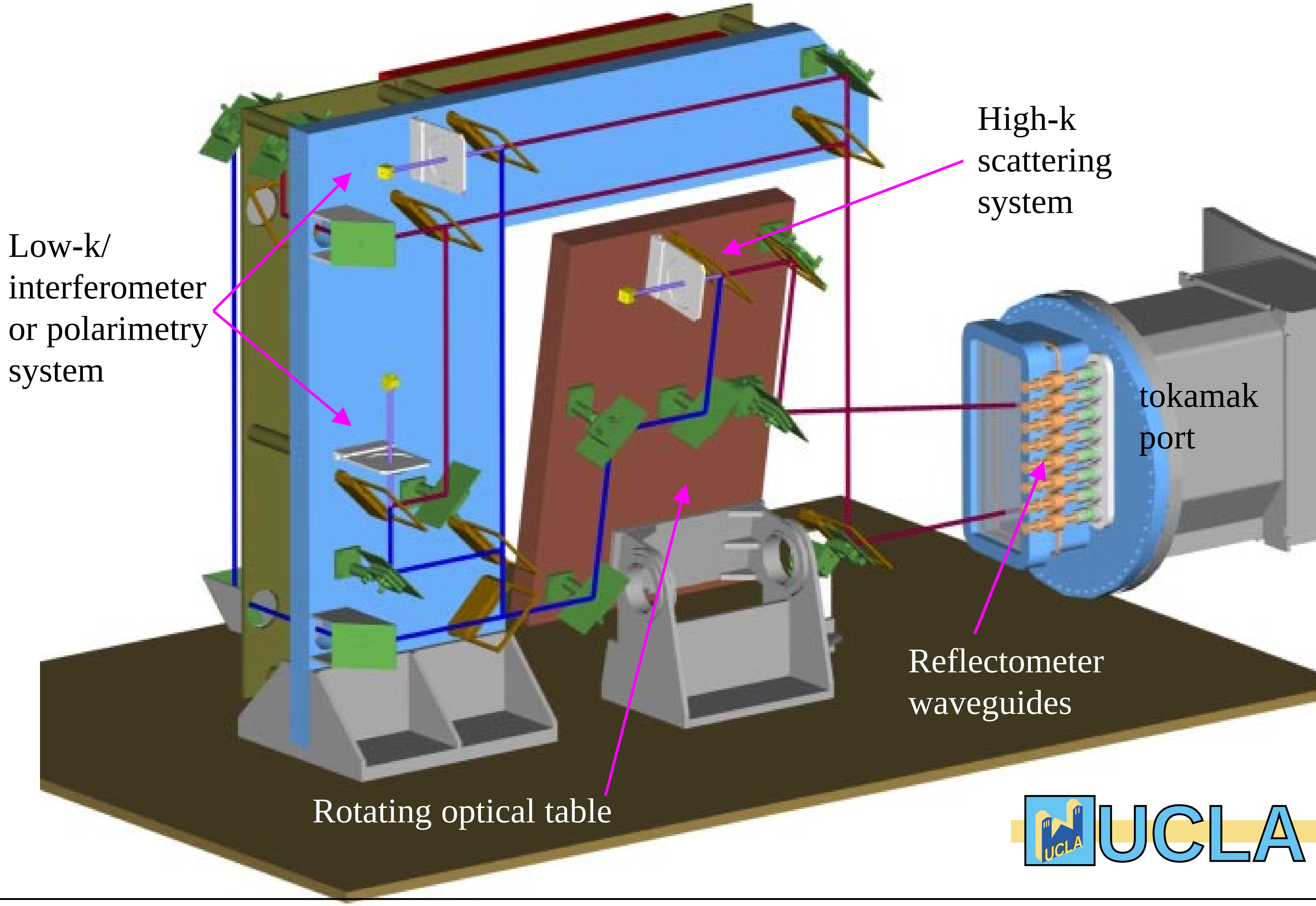


Scattering Spatial Response Function

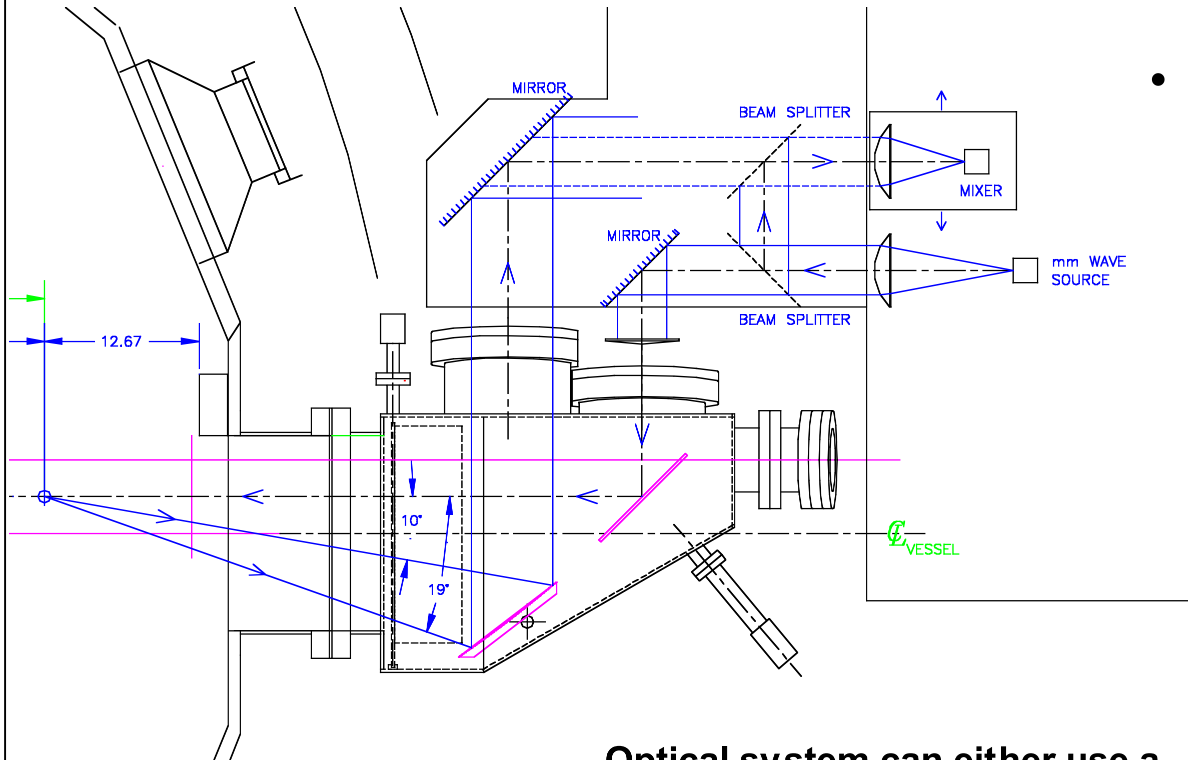


- FIR scattering detects density fluctuations
- Observed wavenumber k_{obs} depends on viewing angle (probe wavenumber = k_0) $k_{obs} = 2\, k_0 \sin(\theta/2)$.
- Spatial resolution depends on k_{obs}.
- Δk depends on beam size a ($\Delta k=2/a$)

Initial 3-D design drawing of integrated high k system



Modification in approach to high k scattering



Scattered radiation with scattering angles from 10 to 19 degrees.

Probes "k"s from ~10 to ~20cm^{-1}

Optical system can either use a single lens and collect full range of wavenumbers.

or

Smaller individual lenses can be used to select different individual "k"s.

- Rather than adopting the concept outlined in a recent DoE proposal, UCLA plans to implement more of an incremental approach so that
  - (1) Believable data at high k might be obtained earlier
  - (2)This data would then guide future system design and lead to an improved system
  - (3) The modified system allows integration into the new vent and run schedule

High-k density fluctuation backscattering

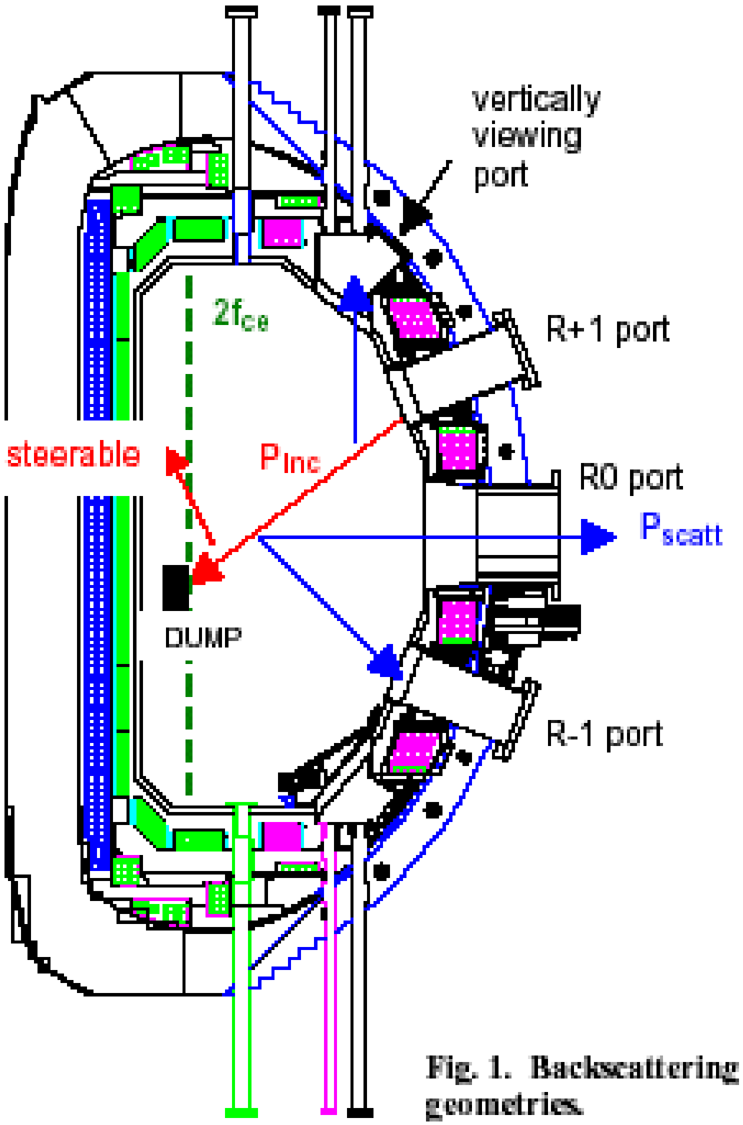
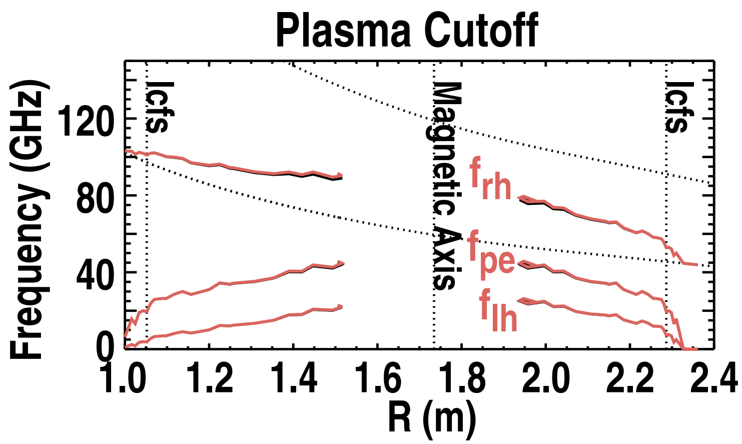
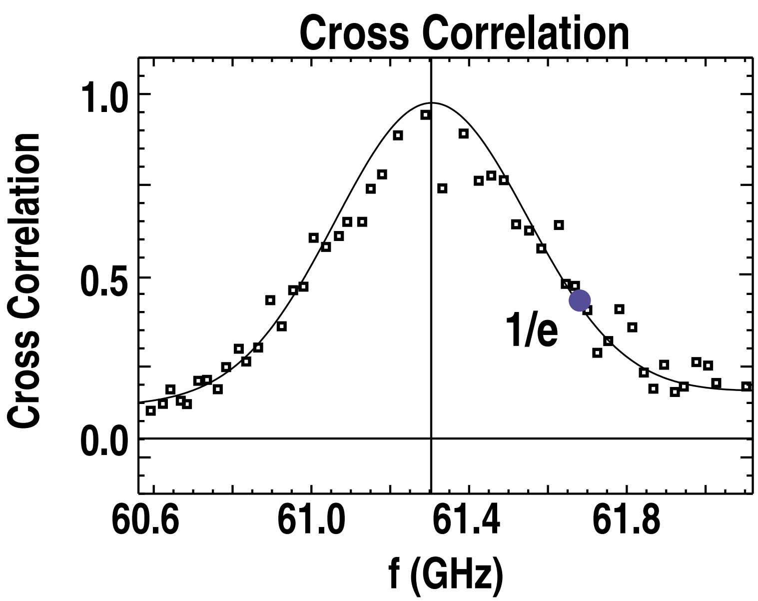


Fig. 1. Backscattering geometries.

- M. Gilmore (UCLA but soon to be at UNM) proposing to measure high-k using combination of ECH waveguides and current reflectometry antennas.
- Depending upon geometry will be k ~ 30-60 cm^{-1}
- Measurement location will initially be on high field side of tokamak.

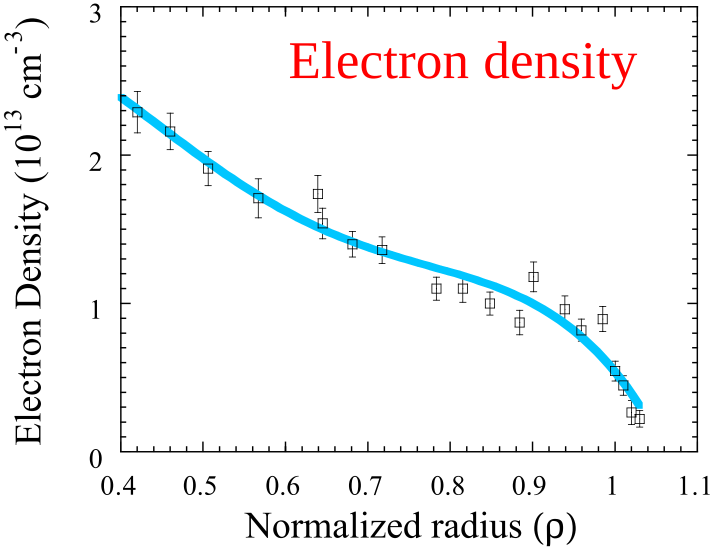
Example: Correlation reflectometry

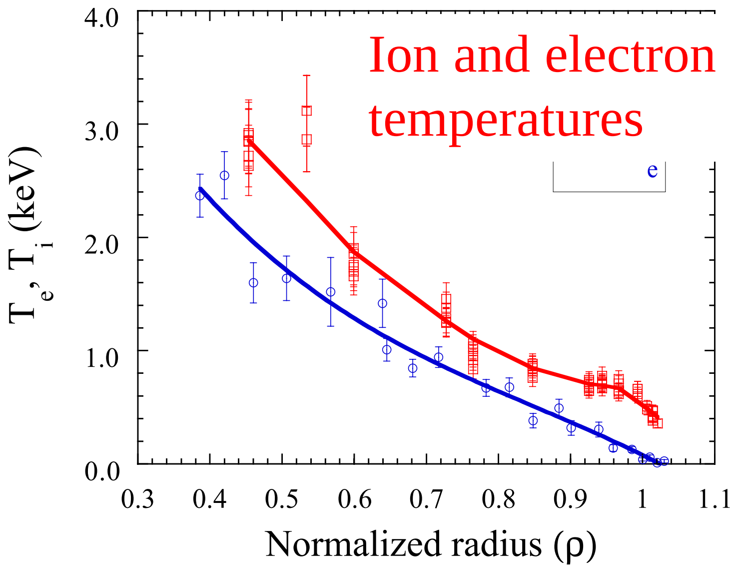




- Turbulence data obtained from correlation reflectometer- radial correlation length.
- Correlation length is a statistical quantity, independent of amplitude thus avoiding some potential calibration issues and making it good comparison quantity.
- Second advantage of system is ability to probe large region of plasma cross-section in many different regimes (Ohmic, L-mode, QDB, etc.)
- Representative cross-correlation shown.

Examine Δr from L-mode plasmas

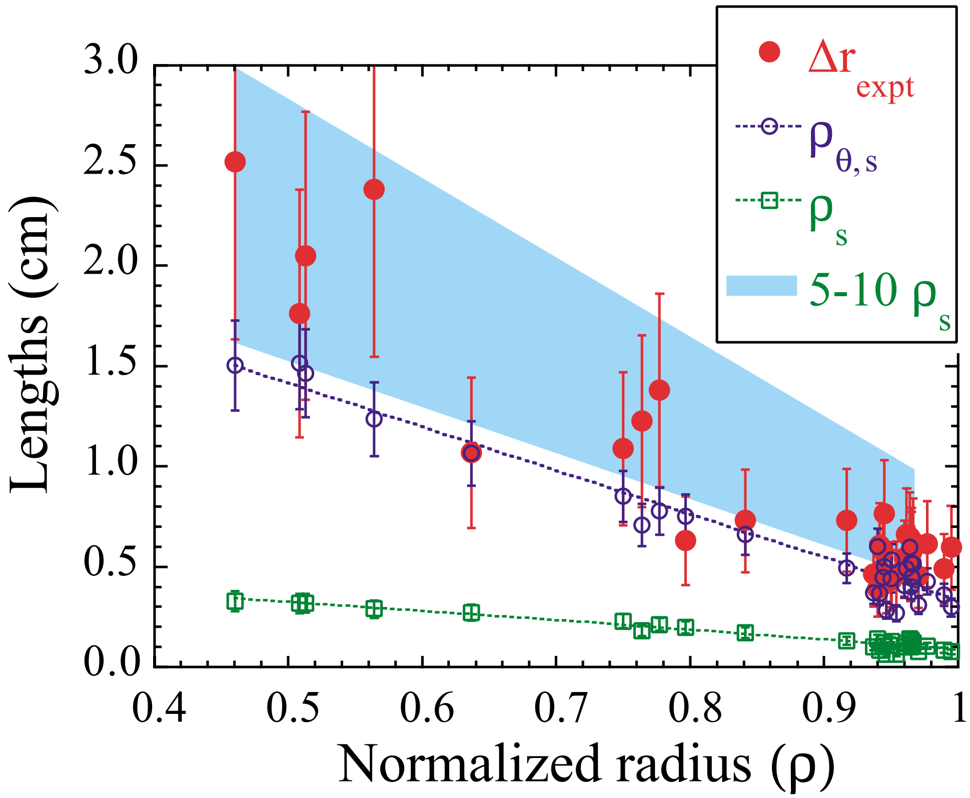




- L-mode discharge - sawteeth avoided via early neutral beams.
- Radial profiles of density and temperatures at the time of interest.
- Plasma in a regime relevant to
  - trapped electron mode ($\rho < 0.9$),
  - collisionless drift wave ($0.9 < \rho < 1$),
  - ion temperature gradient (ITG) mode ($\rho < 1$).

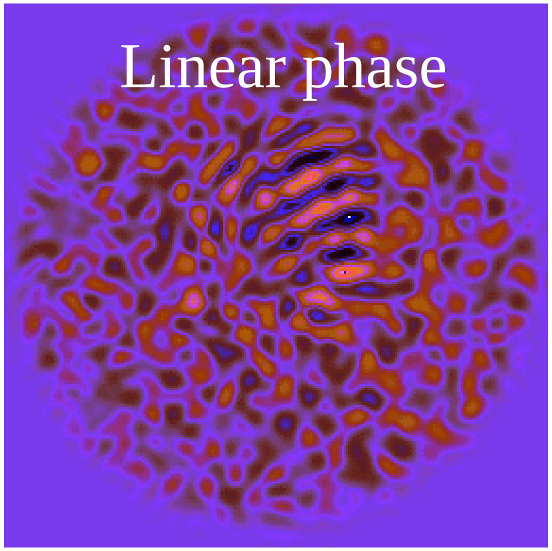
UCLA

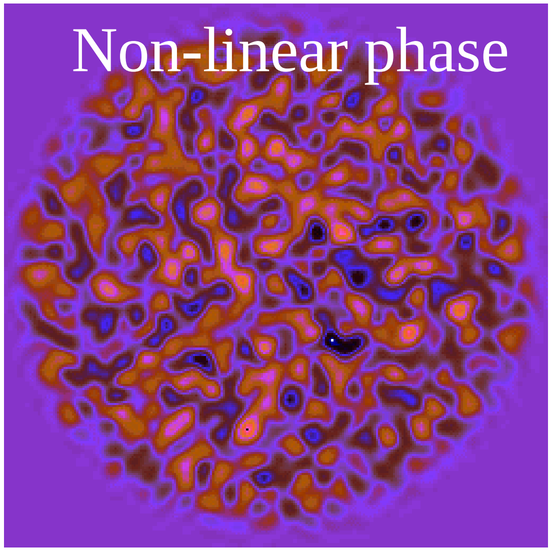
Radial Correlation Length Decreases with Radius



- Δr are 5-10 times larger than ρ_s
  - but are of order poloidal $\rho_{\theta,s}$
- ion sound gyroradii
  - $\rho_s = (m_i T_e)^{1/2} /eB$
  - $\rho_{\theta,s} = (m_i T_e)^{1/2}/eB_\theta$
  - ρ_s important as enters into theoretical predictions of radial correlation lengths Δr.
- Indeterminacy of Δr scaling with $\rho_{\theta,s}$ or $\rho_{\theta,s}$ is interesting and important question which we will return to later.

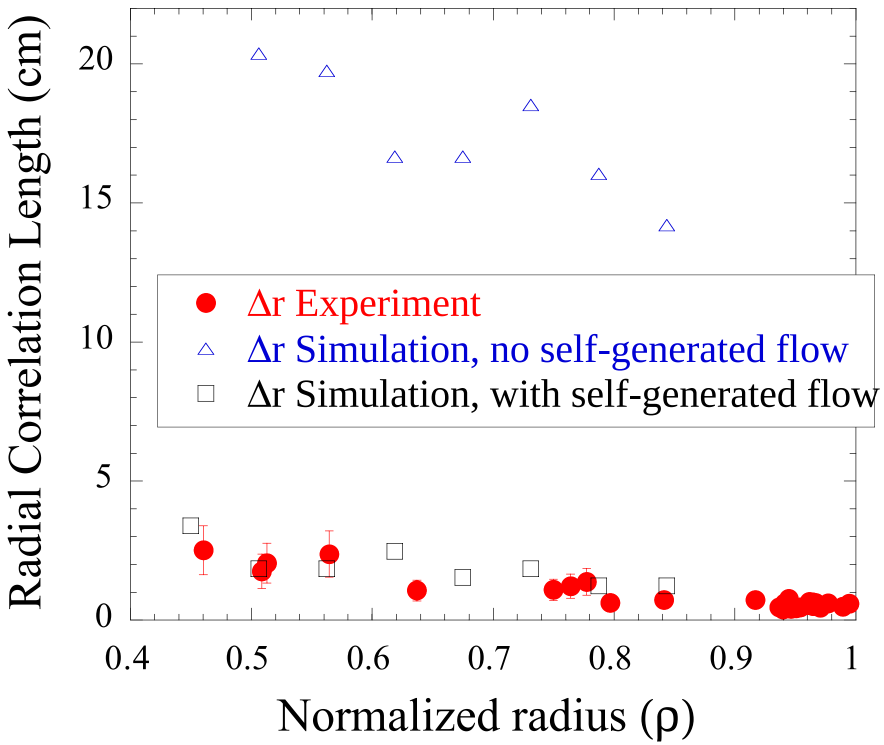
UCAN Turbulence Simulation Code





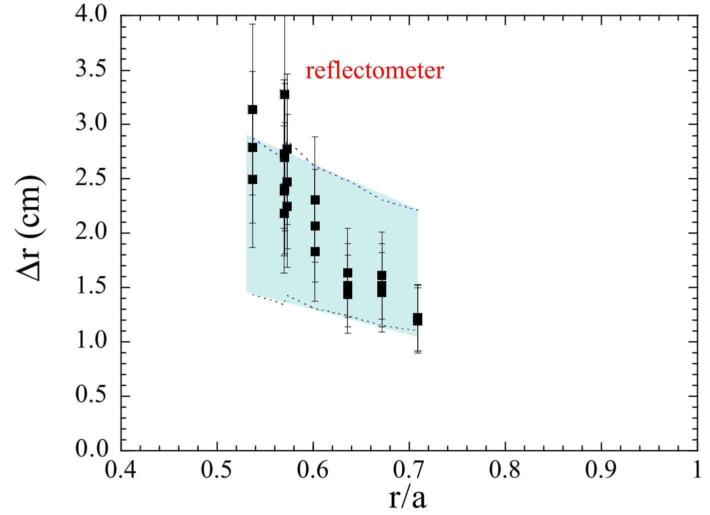
- Massively parallel, nonlinear, toroidal, 3D, global gyrokinetic particle-in-cell (PIC) code developed at UCLA [Sydora, '87] utilized.
- Cartesian coordinates covering whole plasma cross section (or as is numerically feasible).
- Circular cross-section.
- Electrostatic approximation is imposed throughout.
- Adiabatic electrons.
- The nonlinear δf method is applied to solve the gyrokinetic Vlasov-Poisson system of equations.
- Polynomial fits to experimental profiles (n_e, T_i, q, E_r) to set initial equilibrium.

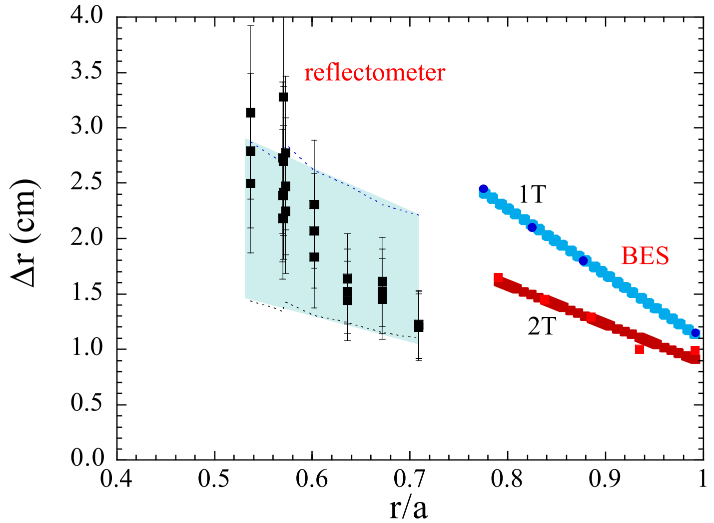
Simulation Produces Similar Results When Zonal Flows Included



- Two different numerical runs shown - with/without zonal flows.
- Without zonal flows Δr are long, spanning most of 65 cm radius.
- With zonal flows Δr drop to near measured Δr in magnitude and radial behavior.
  - Δr reduction with zonal flow also observed in other simulations.
- Zonal flows clearly change turbulence characteristics and are necessary for agreement with experiment.

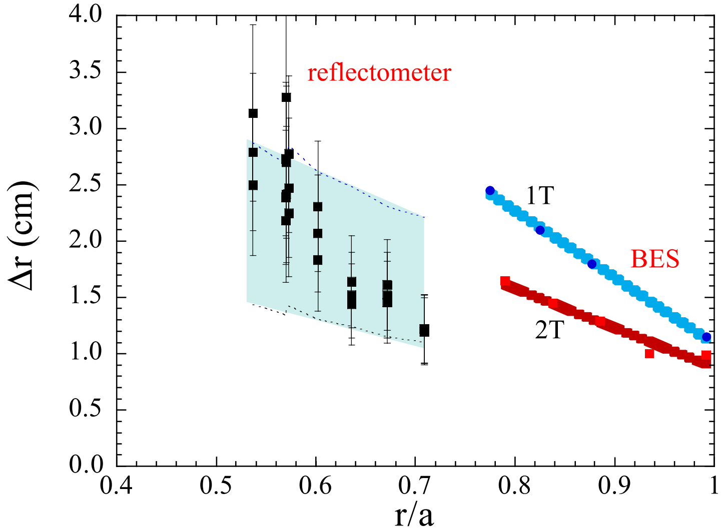
ρ*scaling experiment -Preliminary!

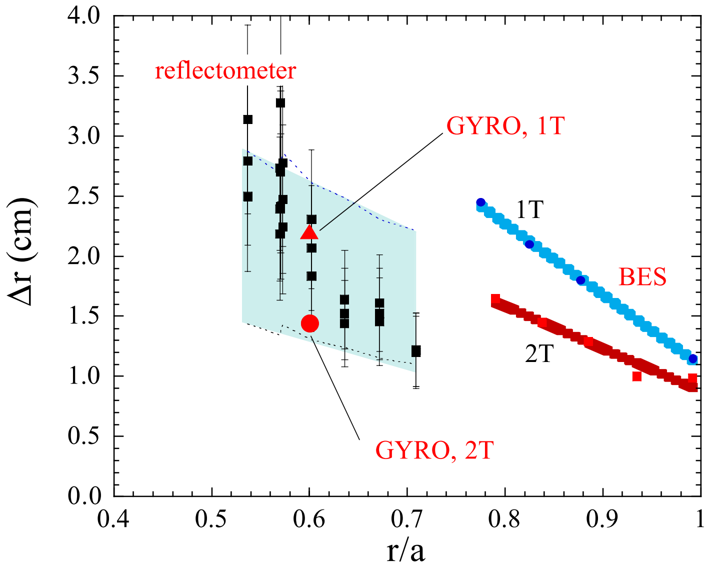




- Reflectometer data in 5-10 ρ_s range.
- Reflectometer and BES data reasonably close given different radial positions.
  - Shots for reflectometer data not matched.
  - No comparable reflectometer data for 1T case.
- Radial variation?
  - Illustrates need for radial profiles from simulation.
- Illustrates experimental problems associated with comparisons - matching spatial location, times, ...

Compare experiment and GYRO for ρ^* scaling experiment -Preliminary!





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- GYRO - kinetic electrons, rotation, shaping, shafranov shift, profile variation, $\beta > 0$

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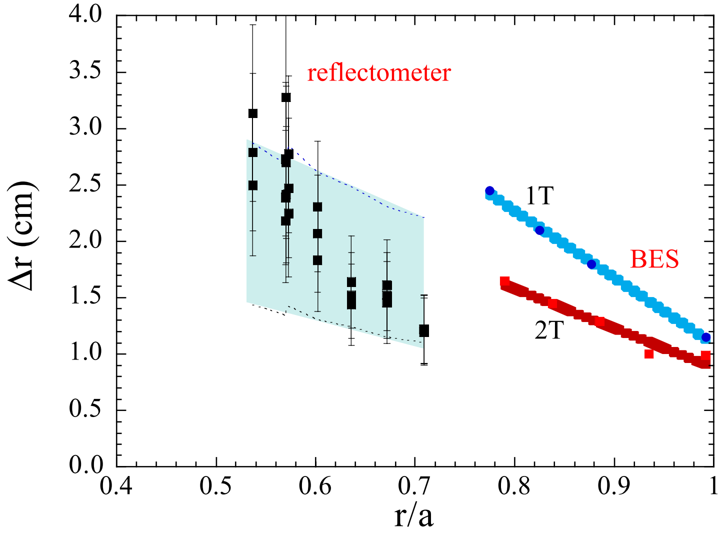

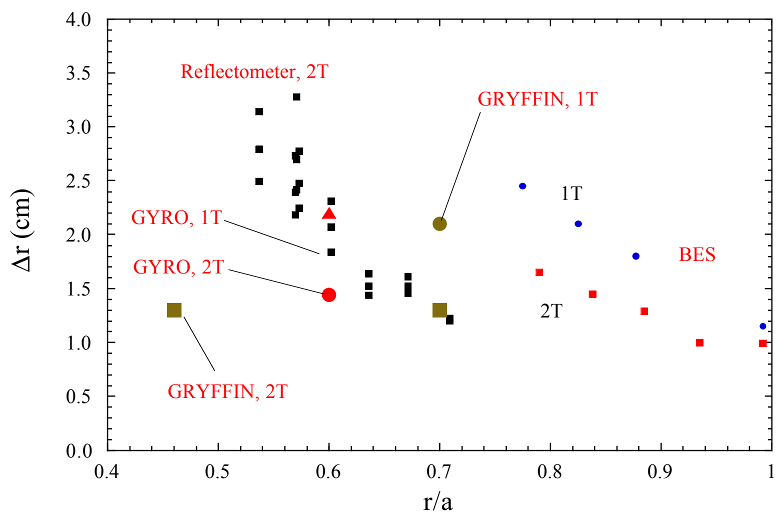

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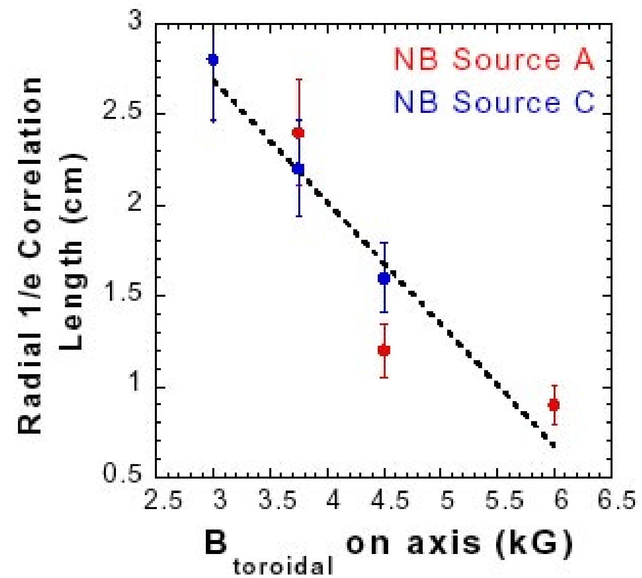
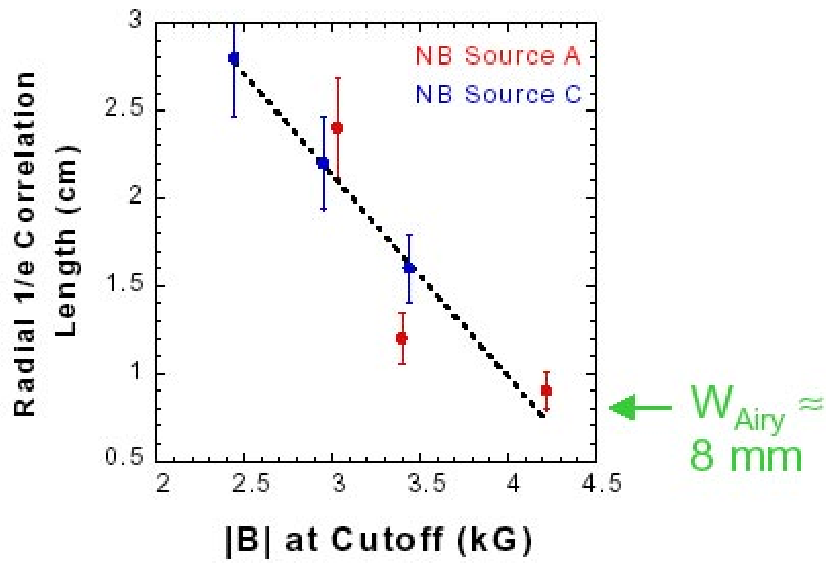
Example: NSTX correlation reflectometer data

Radial Correlation Lengths Vary With Magnetic Field for Fixed I_p/B_{tor} ("Constant q")

Δr versus $B_{toroidal}$ on axis



Δr versus $|\underline{B}|$ at cutoff



- Fixed line avg density, $\overline{nL}$
- B taken from EFIT01
- No apparent changes with NB source A vs. source C

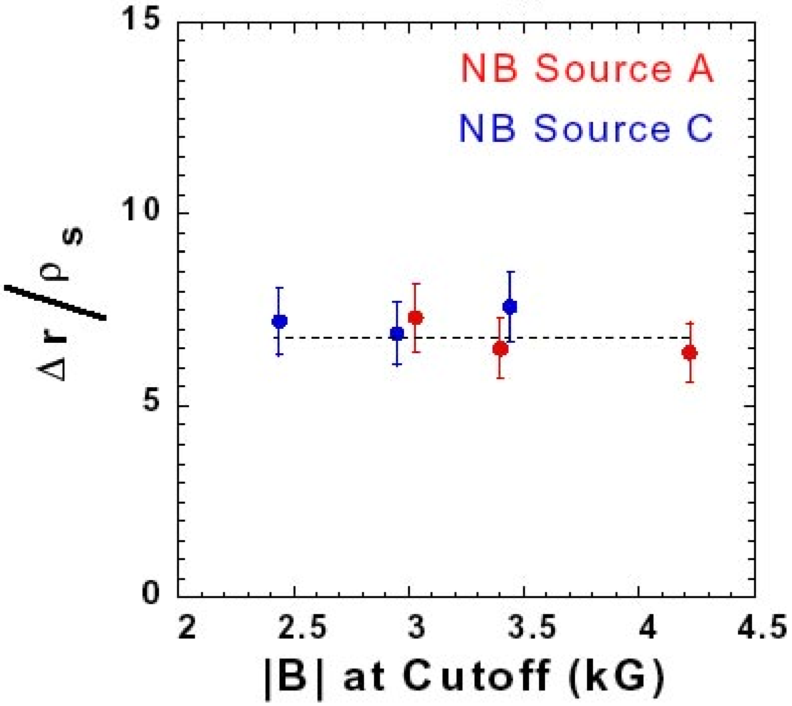
M. Gilmore, UCLA

NSTX data

Radial Correlation Lengths Scale with ρ_s at Fixed I_p/B_{tor} ("Constant q")

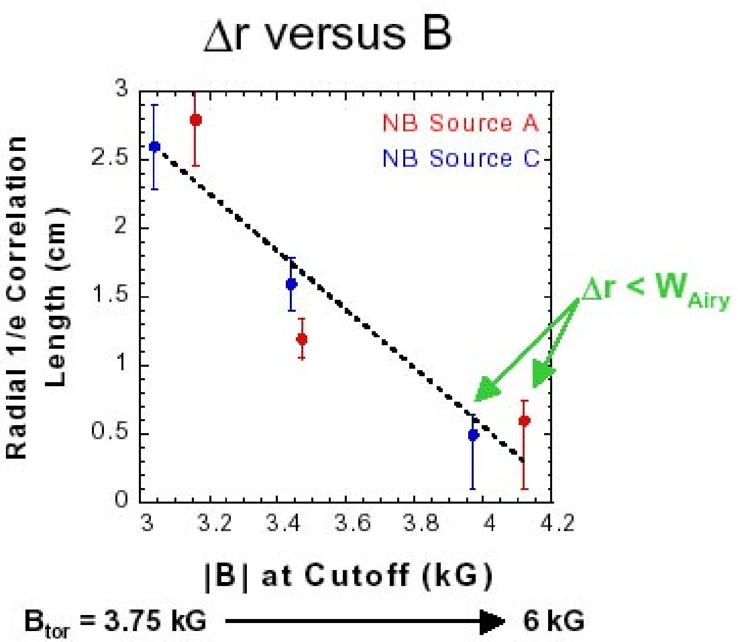
- $\Delta r \approx 6\text{-}7 \times \rho_s$, where $\rho_s \propto 1/|\underline{B}|$
- $\Delta r \approx 4\text{-}5 \times \rho_{s,toroidal}$, where $\rho_{s,toroidal} \propto 1/B_{toroidal}$
- $\Delta r \approx 3\text{-}4 \times \rho_{s,poloidal}$, where $\rho_{s,poloidal} \propto 1/B_z$ at the midplane

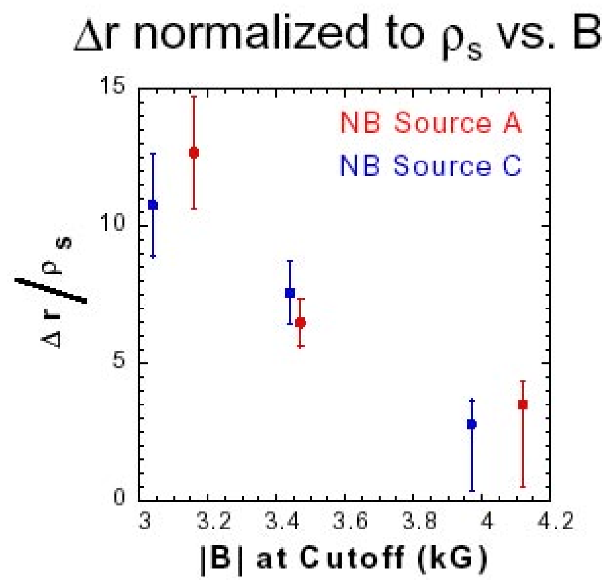
1/e correlation length normalized to ρ_s vs. $|\underline{B}|$



M. Gilmore, UCLA

Normalized Correlation Lengths Decrease with B_{tor} at Fixed I_p (1 MA)



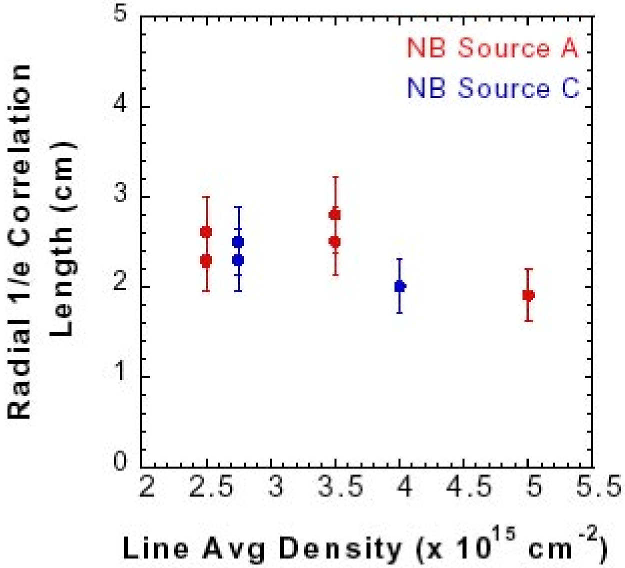


- Δr varies with $|\underline{B}|$ (or B_{tor} on axis), but $\Delta r / \rho_s$ not constant
- scaling by $\rho_{s,toroidal}$, $\rho_{s,poloidal}$ show the same trend

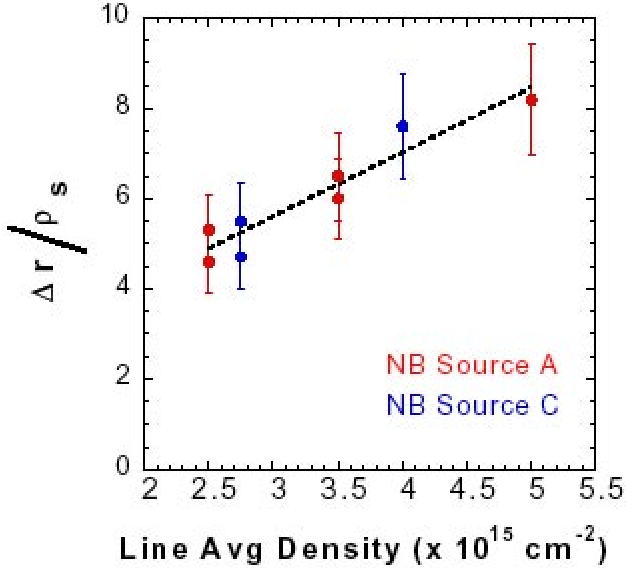
Apparent Increase in Normalized Correlation Lengths with Increasing Line Density

- *Fixed I_p (1 MA) and B_{tor} on axis (4.5 kG)*
- *T_e decreasing as* $\overline{nL}$ increases

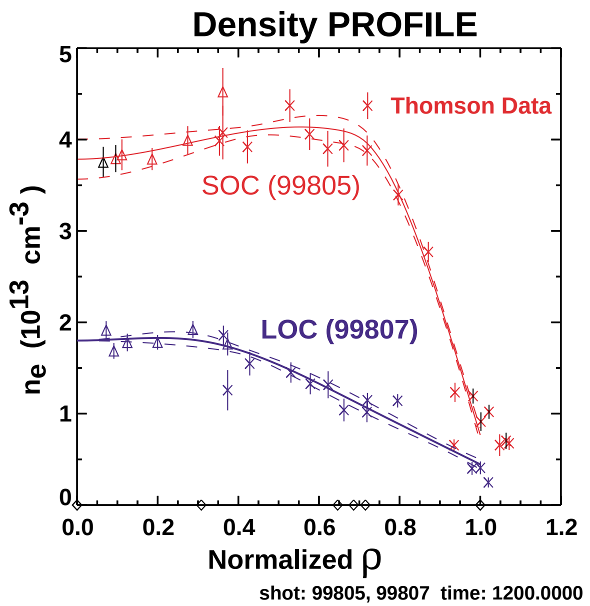
Δr vs. $\overline{nL}$

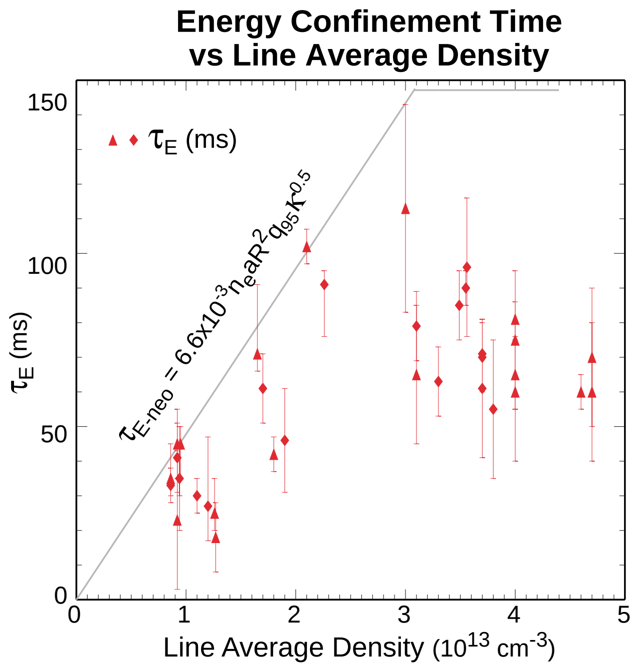


Δr normalized to ρ_s vs. $\overline{nL}$



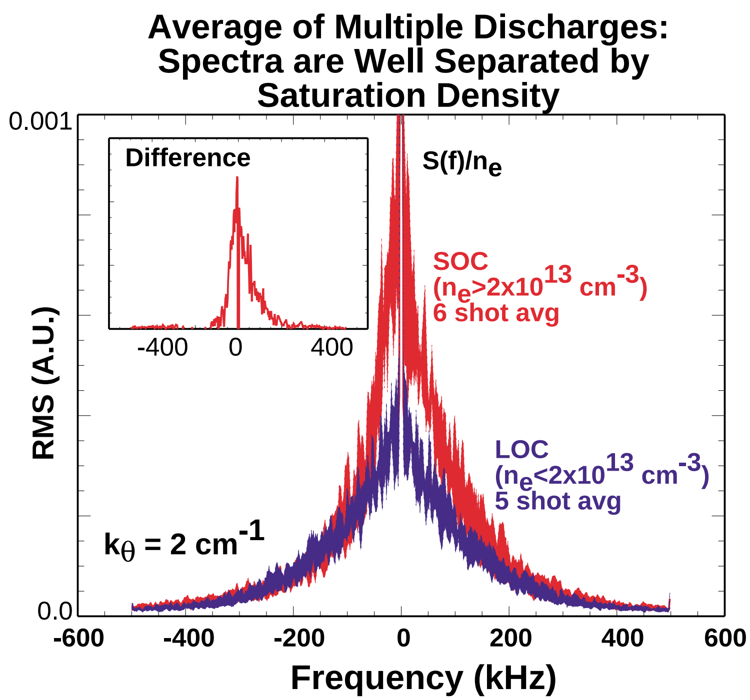
Example: DIII-D Low and high density discharges show different confinement characteristics (Rettig APS 2000)

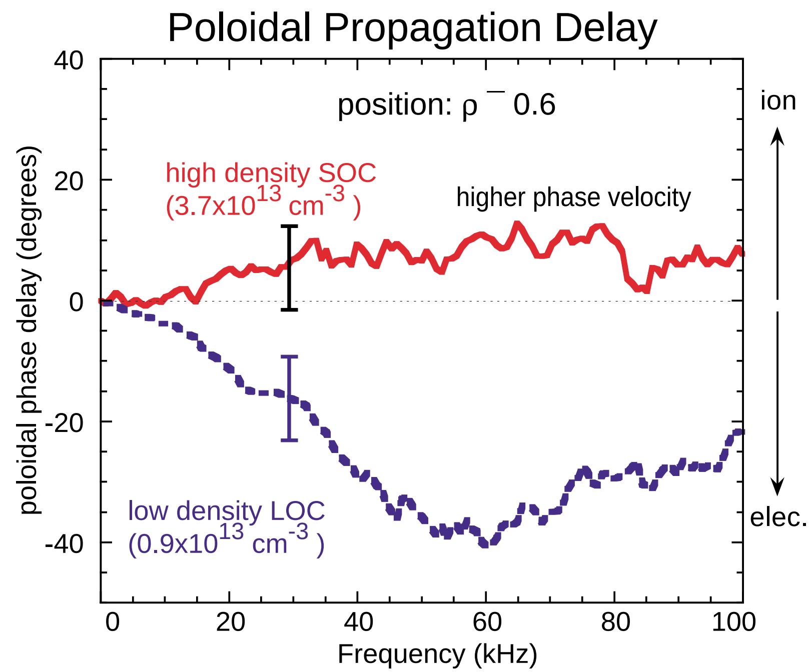




- Circular cross section plasmas used.
- Low and high n_e discharges showed different confinement as well as turbulence characteristics.
  - Energy confinement initially increases with density then saturates.

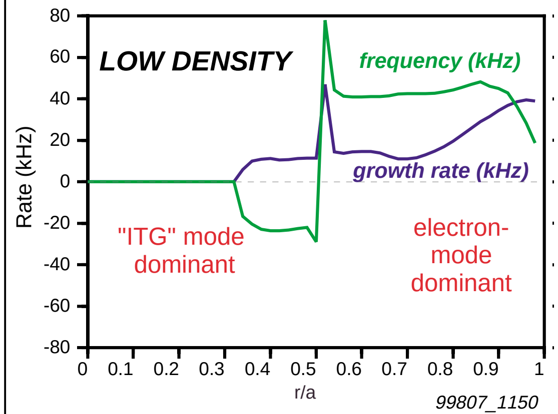
Low and high density discharges also show different turbulence characteristics (Rettig APS 2000)



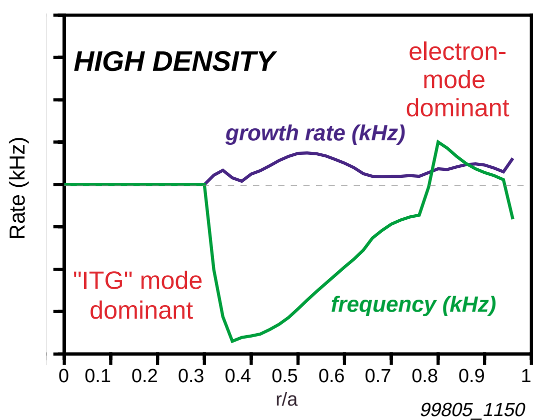


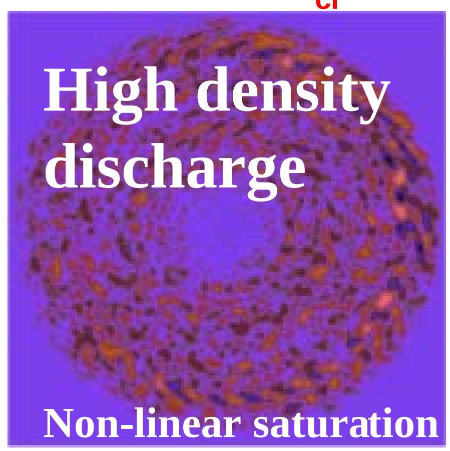
- Appearance of low frequency density fluctuation at higher n_e.
- Poloidal propagation (from reflectometer) shows changes consistent with appearance of ñ propagating in ion diamagnetic drift direction.

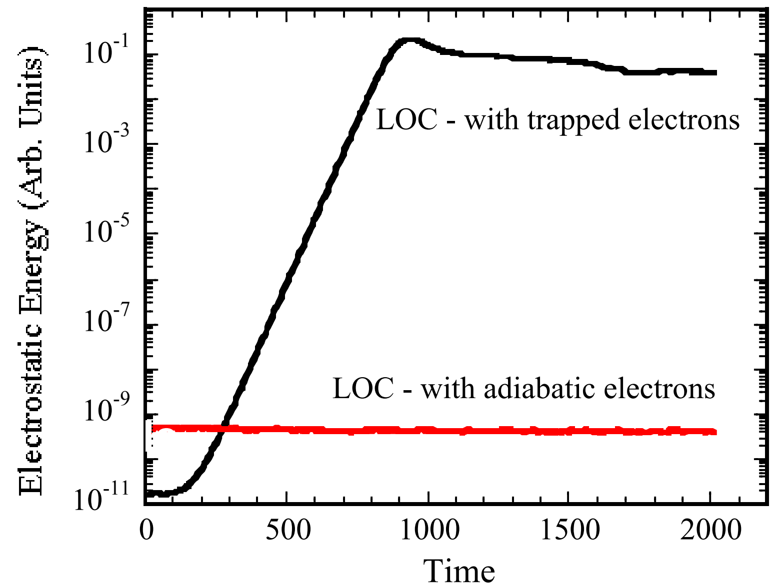
Low density plasma did not go unstable in UCAN simulation due to lack of non-adiabatic electrons



$t=6.8\mathrm{x}10^3/\omega_{ci}$



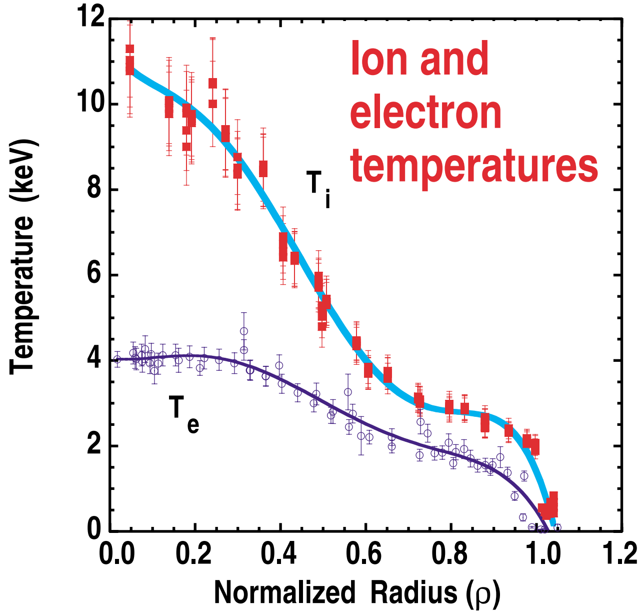


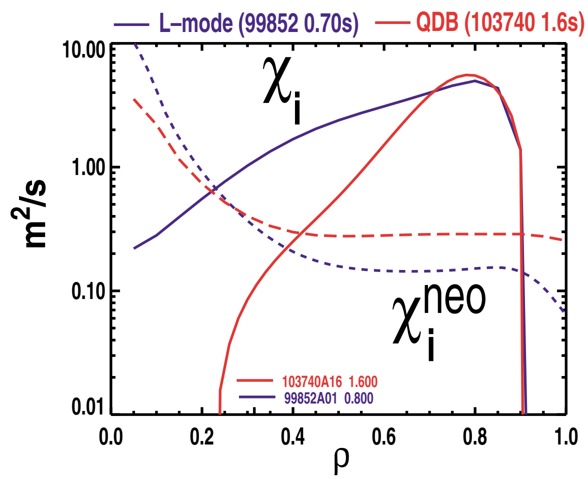


- Time history of electrostatic fluctuation energy shown above.
- Simulation with trapped electrons now goes unstable.
- Resulting instabilities looked like mix of TEM and ITG

Low density case not unstable in previous UCAN simulation.

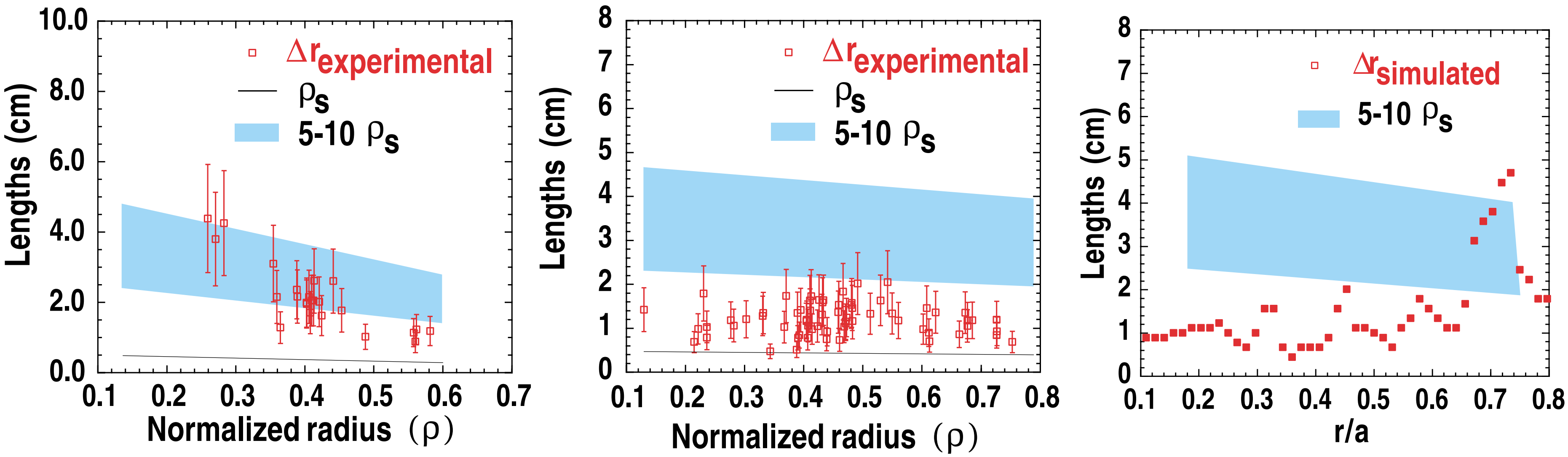
Example: High Performance Plasma (QDB Discharge)





- Quiescent double barrier (QDB) plasmas are high performance plasmas characterized by transport barriers in both edge and core.
- Compared to standard L–mode discharges QDB plasmas show substantial reduction in core electron and ion thermal diffusivities
- Results thought to be consistent with ExB velocity shear decorrelation of turbulence and resulting reduced transport.

Radial Correlation Lengths Shorter in QDB Plasmas



- QDB Δr below values normally seen in L–mode - but still larger than ρ_s.
- Departure from normal L–mode type scaling occurs most clearly for r/a = 0.2-0.5.
- Since Δr often related to transport step length this decrease in Δr is consistent with local decrease in transport levels.
- Simulation Δr similar to experimental data in magnitude and radial behavior.
- Large zonal flows generated in simulation, of order experimental ExB flows.
  - As much as 20 km/s compared to experimental 30 km/s.
- Without zonal flows simulated Δr very long, consistent with picture of shear induced Δr reduction.

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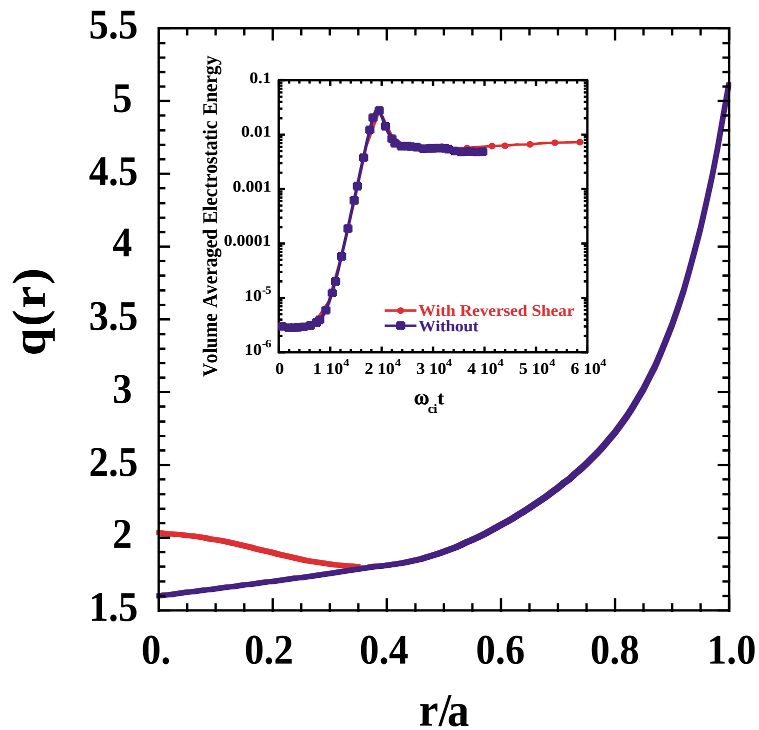
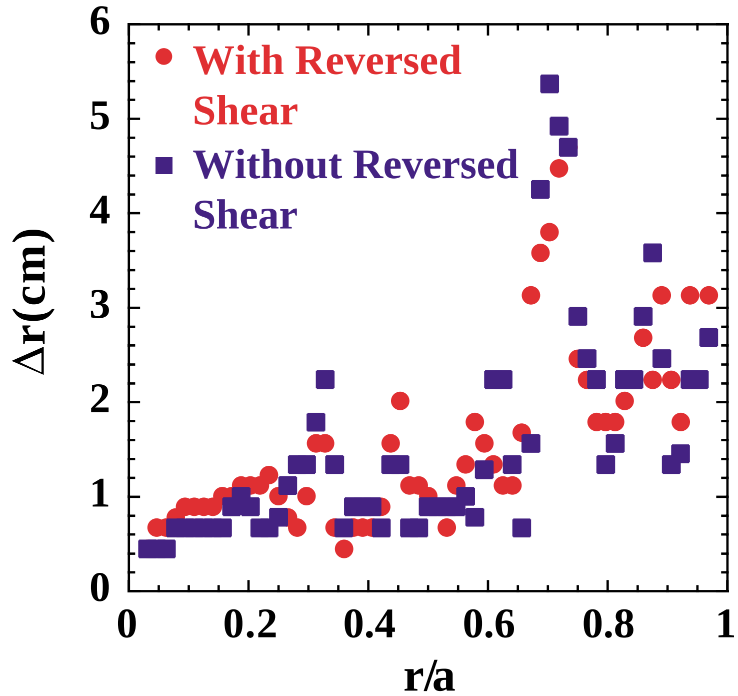
Effect of reversed magnetic shear is weak in simulation





- QDB plasmas have weak negative central magnetic shear
- Simulation shows little difference between two cases.
- What are shortened Δr due to in simulation? Shaping, electrons dynamics, …?

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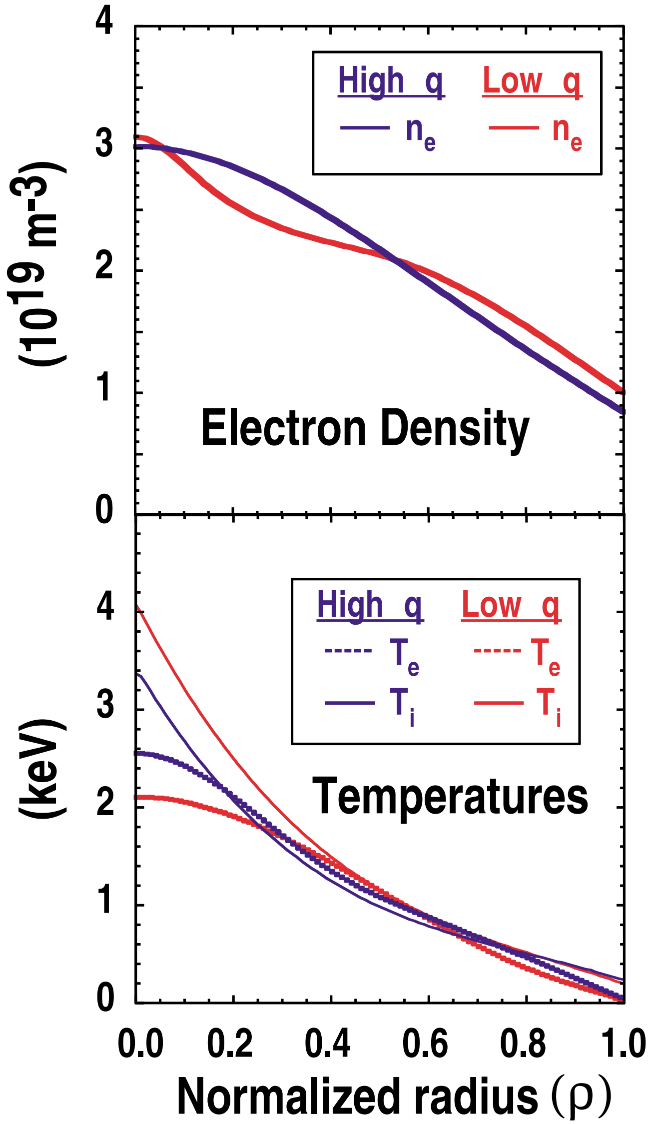
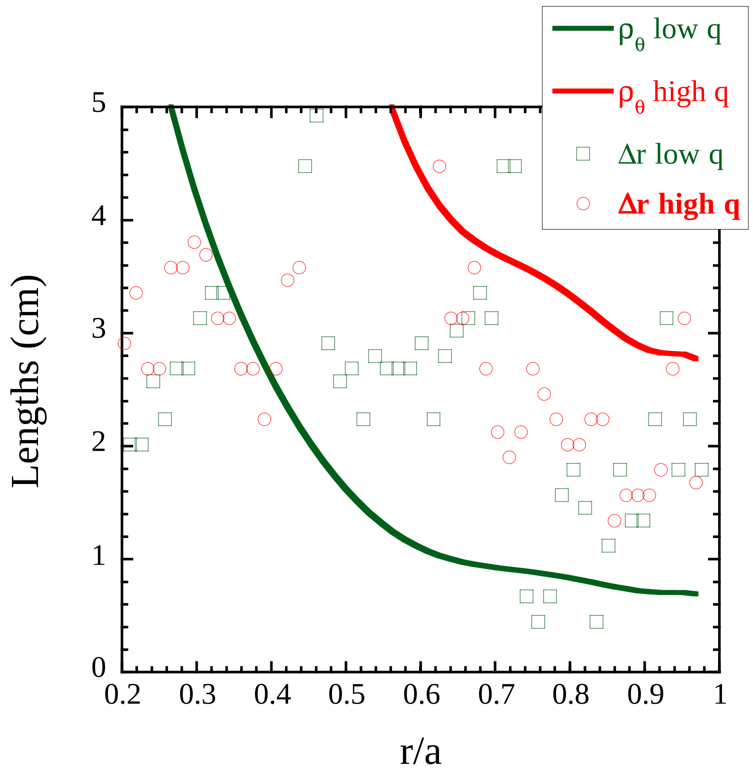
Example: Does Δr scale with ρ_θ or with ρ_s?



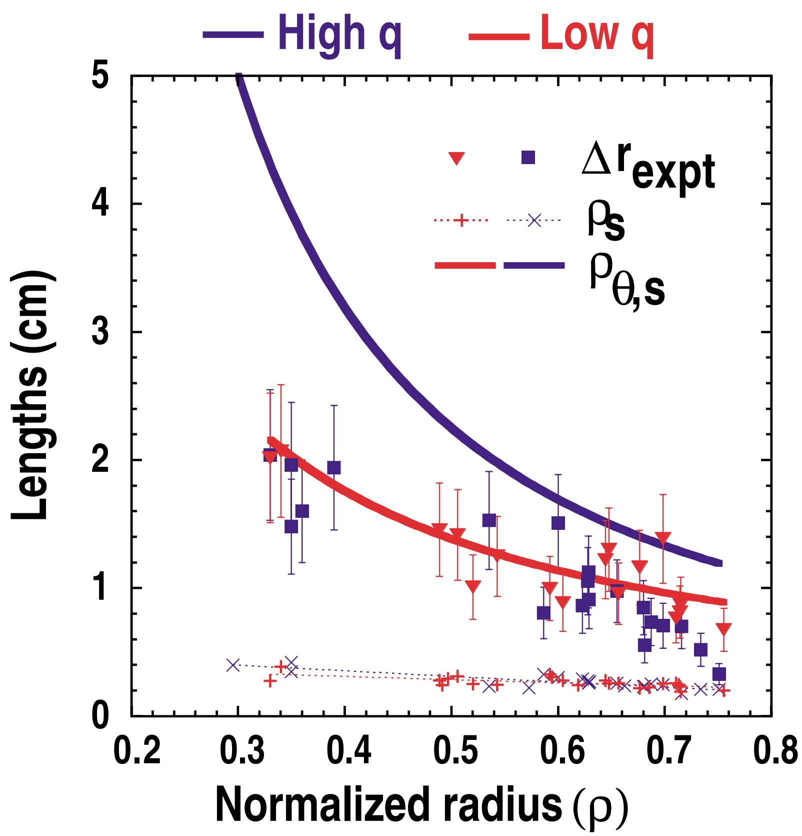
- Uncertainty between Δr scaling with $\rho_{\theta,s}$ or 5-10 ρ_s was intriguing.
- Pointed to possible trapped particle effect via $\rho_{\theta,s}$.
- Also several analytic theories have $\rho_{\theta,s}$ dependence.
- Previously found $\Delta r \sim \rho_i$ (McKee, 2001).
  - Experiment was at constant q.
  - Results could be due to B or B_θ.
- Experiment to investigate rq,s scaling and to break indeterminacy.
- L–mode plasmas, varied B_θ via Ip.

Simulation Predicted No Strong Scaling With ρ_θ



- Prior to experiment simulations performed to predict Δr variation with ρ_θ.
- L-mode conditions, q value varied by factor of 4.
- Found no clear variation of Δr with ρ_θ - similar to experiment.
- In simulation, q also varied by changing major radius R (via $q=rB_z/RB_\theta$).
  - Some weak evidence of Δr variation observed, presumably due to major radius variation.
  - This effect will be numerically tested more fully in the future.

Correlation length not strongly dependent on ρ_θ



- Found no clear variation of Δr with change of ~ 1.8 in ρ_θ.
- $\Rightarrow$ Scaling found previously was indeed with B_0 and ρ_s

Needs and questions

- High-k simulations - diagnostics coming on line, DIII-D, NSTX
- Magnetic fluctuation simulations ? - diagnostic planned, within 1-2 years
- T_e fluctuation simulations - measurements possibly next run period.
- Shaping
  - Affects QDB simulations on DIII-D?
  - NSTX simulations needed.
- Electron dynamics - clearly affects some results, QDB?.
- Most measurements are n_tilde, some Te_tilde, B_tilde
  - Code differences between n_tilde and phi_tilde?

Observations and Issues

- "Qualitative vs quantitative"
  - Correlation lengths, spectral shapes, changes in ñ, fluxes, etc. with plasma parameters.

    versus
  - Absolute ñ, fluxes, etc.
  - Is one class more appropriate or better than other?
- Multi-point vs single point
  - Agreement/disagreement in restricted radial range probably not enough.
  - Scalings with plasma parameters, e.g. non-dimensional scalings needed but again more than one radial position.

Observations and Issues

- Time vs space
  - Experiments have lots of time points, good statistics, limited spatial points.
  - Simulations with lots of spatial points, limited time
    - Can simulations utilize extra spatial points as proxy for time?
      - Similar to using increased number of time realizations in time series analysis.
- Fluxes vs diffusion coefficients
  - Fluxes (heat and particle) more directly related to experimental measurements.

Bookkeeping and small things that can take a lot of time

- Common Definitions
  - RMS levels: $Y_{RMS}^2 = < [Y - < Y >]^2 >$ where <…> is a time average over an agreed upon time T.
  - ñ/n, T_tilde/T, ϕ_tilde/T all normalized to local values of n and T, where the tilde ~ indicates an RMS value.
  - Spectra $P_{YY}(f) = \Im(Y) \cdot \Im^*(Y)$ are power not amplitude.
  - Correlation lengths: 1/2 power vs 1/e widths.
- Input of experimental info, profiles into code
  - e.g. EFIT data, density, Te, velocity profiles
  - Ease of input
  - Error checking

Future Experimental Measurements

- n_tilde - Te_tilde phase?
- k_parallel?
- more globally extended measurements of zonal flow?
- Others?